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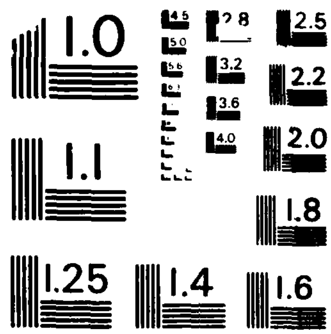
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Space-time correlation measurements of two velocity components in the wall region of a turbulent pipe flow. The third component was obtained from continuity, and eigenfunctions of the cross-spectral density tensor extracted.

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A Study of Turbulent Boundary Layer Structure

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The purpose of this investigation was to complete analysis of measurements in the wall region of a turbulent pipe flow, which had been begun under other sponsorship. The investigation was supported by the David W. Taylor Naval Ship Research and Development Center, through its General Hydrodynamics Research Program, from 10/1/72 through 9/30/77. From10/1/77 through 4/30/80 the investigation was supported internally by the Fluids Engineering Unit of the Applied Research Laboratory, the Pennsylvania State University, which is supported by the Naval Sea Systems Command. From 5/1/80 through 5/31/82 support for the investigation was provided by NASA/Ames Research Center. Digitization of the tapes was provided courtesy of the NASA/Langley Research Center.

The motivation for these measurements arises from our current understanding of various schemes to modify the wall region (the region closest to the wall) of a turbulent boundary layer, resulting in drag reduction. This understanding suggests that normal boundary layers and drag reducing boundary layers in liquids containing polymer additives or microbubbles, or in flows over riblets, all have similar mechanisms. In all these flows the indications are that the structure of the flow in the wall layer is not changed, but the scales are increased. In all these flows, large counter-rotating eddy pairs alligned with the mean flow are observed, which sweep up slow-moving fluid from near the wall, creating a temporary, local inflectionary profile in the streamwise velocity. Some sort of secondary instability is observed to arise from this inflectionary profile, leading to an intense burst of higher wavenumber turbulence, making a large contribution to the Reynolds stress. This is felt to be the basic dynamical mechanism responsible for the maintainance of the turbulent boundary layer. In the various drag-reducing flows, the eddies are observed to be larger, and to extend farther from the wall. It was felt that a better understanding of the dynamics of these large eddies in the wall region of a turbulent boundary layer might lead to better control over existing drag reduction schemes, and to the possibility of devising new drag reduction schemes. Experimental evidence and theory indicate that there is no difference between the wall regions of a turbulent boundary layer and of a turbulent pipe flow. Since the latter is easier to set up experimentally, we decided to make the measurements in a pipe flow.

The experimental measurements were completed at the end of July, 1980. These consisted of two-point velocity measurements carried out with two hot split-films, each capable of determining two components of the local, instantaneous velocity vector. A total of about 1450 different spatial arrangements between the two probes were realized (six lateral and radial spacings, and seven streamwise), approximately three minutes of data being recorded at each configuration, corresponding to about 4000 integral scales. These data occupied approximately 100 reels of 9 track magnetic tape.

The required analysis was complex. We wished to extract the first few eigenfunctions of the spectral density tensor. It can be shown that the instantaneous velocity field can be represented in terms of these eigenfunctions, and that such a representation converges faster than any other representation. We feel that we can identify the first eigenfunction with the observed large eddies. This belief is based on previous measurements made by Bakewell under Lumley's direction (see Herzog, 1985 for all references). These were similar to the measurements of Herzog, but measured only one velocity component, over a considerably smaller spatial extent. Nevertheless, the analysis used was the same, and with some assumptions to replace the missing velocity components, the eigenfunctions found resembled the large eddies observed in visualizations.

To analyze Herzog's data, first the tapes were digitized, producing more than three hundred raw digital tapes. The tapes were sorted manually to identify valid data runs, eliminate duplications and label segments in a machine identifyable way. The sorting produced about one hundred twenty final, properly labeled tapes. Then, the space-time correlations between the variables were generated, interpolated and smoothed. The third, unmeasured component was then generated by solution of a differential equation obtained from the continuity condition. Fourier transforms of the correlation matrix were generated, and the first few eigenfunctions of the spectral density tensor were extracted.

This work was completed by September, 1985 with support from Cornell. It forms the Ph. D. Thesis of Siegfried Herzog (see Herzog, 1985 below). Reference should be made to Herzog (1985) for all details of this work. We are in the process of preparing several papers based on Herzog (1985). The eigenfunctions found by Herzog again resembled flow visualization results, as well as results obtained from exact simulations of turbulent channel flow.

In the meantime, we are continuing work on the turbulent boundary layer with support from the Office of Naval Research through the Select Research Opportunity IV Program under Michael Reischman. In particular, we are pursuing a dynamical systems approach to the dynamics of the eddies in the wall region of a turbulent boundary layer. The eigenfunctions extracted from his mountain of data by S. Herzog form the heart of this program. We expand the instantaneous velocity field in the wall region in these eigenfunctions, obtain ordinary differential equations for the coefficients by Galerkin projection, and investigate the properties of this set of equations. The Herzog eigenfunctions are essential, since their optimally fast convergence permits the maximum truncation. This approach has been extremely productive: we have found intermittent behavior which mimics the bursting and ejection phases of wall-region observations, shedding light on, among other things, the question of whether bursting scales with wall region or outer layer variables. Our analysis can easily be extended to various drag reduction schemes by the introduction of variable viscosity and density, and different boundary conditions.

Publications Directly Related to this Grant

Aubry, N., Holmes, P., Lumley, J. L. and Stone, E. 1987. The dynamics of coherent structures in the wall region of a turbulent boundary layer. *J. Fluid Mech.* Submitted.

Aubry, N., Holmes, P., Lumley, J. L. and Stone, E. 1987. Models for coherent structures in the wall layer. In: *1st European Turbulence Conference*, eds. G. Comte-Bellot *et al.*, Berlin/Heidelberg: Springer. Submitted.

Herzog, S. 1985. *The large scale structure in the near wall region of turbulent pipe flow* . Ph. D. Thesis, Cornell University. Also Sibley School of Mechanical and Aerospace Engineering Report No. FDA-86-07.

Presentations Directly Related to this Grant

Aubry, N., Holmes, P., Lumley, J. L. and Stone, E. Models for coherent structures in the wall layer. 1st European Turbulence Conference. Lyon, France, July 2, 1986.

Aubry, N., Holmes, P., Lumley, J. L. and Stone, E. Models for coherent structures in the wall layer. Workshop on ocean surface wave dynamics, Woods Hole, August 6, 1986.

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